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VIBRATION MEASUREMENTS IN A RHIC QUADRUPOLE AT CRYOGENIC TEMPERATURES*

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Abstract

One of the concerns in using compact superconducting magnets in the final focus region of the ILC is the influence of the cryogen flow on the vibration characteristics. As a first step towards characterizing such motion at nanometer levels, a project was undertaken at BNL to measure the vibrations in a spare RHIC quadrupole under cryogenic conditions. Given the constraints of cryogenic operation, and limited space available, it was decided to use a dual head laser Doppler vibrometer for this work. The performance of the laser vibrometer was tested in a series of room temperature tests and compared with results from Mark L4 geophones. The laser system was then used to measure the vibration of the cold mass of the quadrupole with respect to the outside warm enclosure. These measurements were carried out both with and without the flow of cold helium through the magnet. The results indicate only a minor increase in motion in the horizontal direction (where the cold mass is relatively free to move).

INTRODUCTION

Compact superconducting quadrupoles are being considered for use in the final focus region of the International Linear Collider (ILC) [1]. These magnets must meet stringent requirements of the stability of the magnetic field center at nanometer level. One of the concerns in using superconducting magnets is the influence of the cryogen flow on the vibration characteristics of the magnets. Since very little is known about vibration of superconducting magnets at nanometer levels, as a first step, a project was undertaken at BNL to measure the vibrations under cryogenic conditions in a spare arc quadrupole built for the Relativistic Heavy Ion Collider (RHIC) [2]. The cross section of the magnet cold mass in its cryostat is shown in Fig. 1. The cold mass is supported by vertical posts, but is not constrained in the horizontal direction. Even though this magnet is not designed to minimize vibrations, and has a construction very different from that foreseen for the ILC, the present exercise has proved beneficial in developing suitable vibration measurement techniques.

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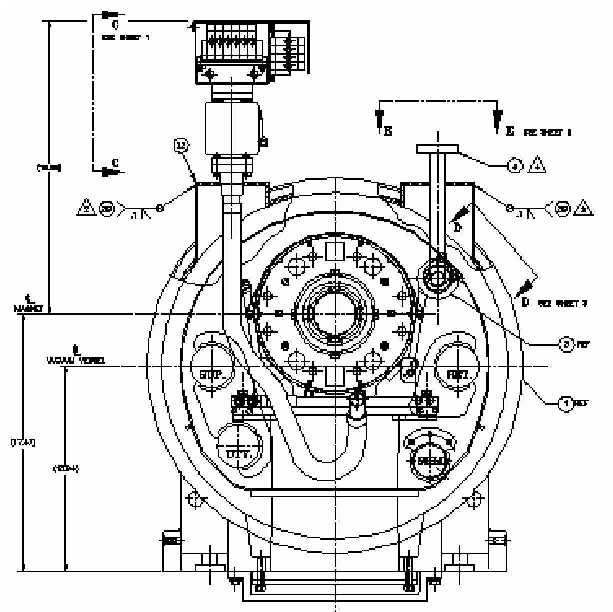

Fig. 1 Cross section of a RHIC quadrupole cold mass in its cryostat.

Given the constraints of cryogenic operation, and limited space available, it was decided to use a commercially available dual head laser Doppler vibrometer for this work. The performance of the laser vibrometer was tested in a series of room temperature tests and compared with the results from geophones. The laser system was then used to measure the vibration of the cold mass of the quadrupole with respect to the outside warm enclosure. These measurements were carried out both with and without the flow of cold helium through the magnet. The results indicate only a minor increase in motion in the horizontal direction (where the cold mass is relatively free to move).

MEASUREMENT TECHNIQUE

Geophones with suitable characteristics provide a reliable means to measure vibrations. However, nearly all such instruments are very bulky and cannot work at cryogenic temperatures. Furthermore, these cannot work in the presence of magnetic field. Given the constraints of cryogenic operation, and limited space available, it was decided to employ an optical interferometric technique to measure the vibration in this work. Even though the magnet was not powered in the present tests, the optical techniques employed can be used even in the presence of a magnetic field. After a careful review of the commercially available laser systems, a dual fiber-optic head laser Doppler vibrometer model OFV-552 with a model OFV-5000 controller from PolyTec Inc.[3] was selected for this work. The performance of the laser vibrometer was tested in a series of room temperature tests and compared with results from Mark L4 geophones [4]. It was clear from these preliminary tests that the motion of the laser head itself could be a serious limitation to the accuracy of the results. The choice of a dual head laser system allows more reliable differential measurements between two objects provided the motions of the two arms of the laser interferometer can be kept the same. The laser system was used to measure the vibration of the cold mass of the quadrupole with respect to the outside warm enclosure. These measurements were carried out both with and without the flow of cold helium through the magnet while the cold mass was maintained at or near 4.5 K. A comparison of the vibration spectra with and without helium flow reveals any significant increase in the vibration as a result of cryogen flow.

All measurements were carried out with the laser vibrometer set to the most sensitive range of 1 mm/s per Volt. The analog output from the OFV-5000 controller was amplified (20X to 500X) and recorded using a 16-bit ADC at a rate of 1600 Hz for a period of 143.5 seconds. The data were Fourier analyzed in blocks of 32K points (0.05 Hz resolution) or 16K points (0.1 Hz resolution) with a Hanning window and 50% overlap between successive data blocks. Each run of 143.5 seconds thus provides many power spectra, which were averaged.

LASER SYSTEM PERFORMANCE TESTS

The first performance test carried out was a measurement of the intrinsic noise in the system. For this test, both the beams of the laser system were terminated with a small mirror. Neglecting any small motion of the mirrors themselves, the laser vibrometer output is expected to be ideally zero. The measured power spectrum is shown in Fig. 2. The noise is less than 1 nm/√Hz for all frequencies above 2 Hz. A few isolated peaks are seen at higher frequencies, but the total RMS motion for any peak is below 1 nm. The total integrated noise is ~2 nm for frequencies above 1 Hz, and is below

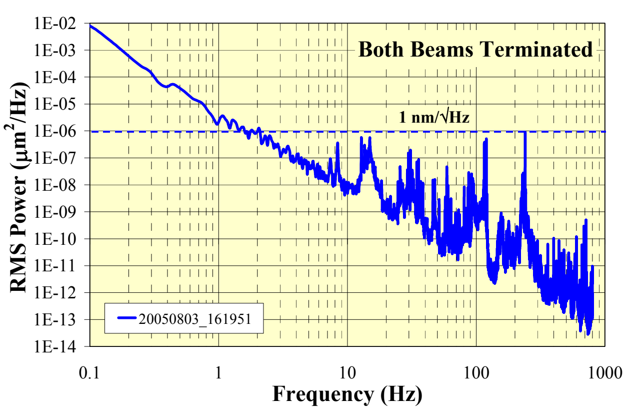

Fig. 2 Intrinsic noise of the laser system, as measured by terminating both beams with a small mirror.

1 nm for frequencies above 10 Hz. These noise figures are well below the typical motion of the magnet on our test stand. It should be noted that the mirrors are perhaps not entirely vibration free at sub-nanometer level. So, some of the high frequency peaks may even be due to mirror motion.

The performance of the laser system was studied next in the single beam mode using a specially built laser head holder and comparing results with the geophone data. For these tests, the reference laser beam was terminated with a mirror. The measurement beam head was mounted in a specially built holder placed on a table, as shown in Fig. 3. The laser beam was used to measure the motion of a large granite table. One geophone was used to independently measure the motion of the granite table, and another geophone was used to measure the motion of the laser holder itself. In the single beam mode, the measurements are sensitive to the motion of the laser head. The output from the laser vibrometer is expected to match the relative motion of the granite table and the laser holder, as deduced from the data from the two geophones.

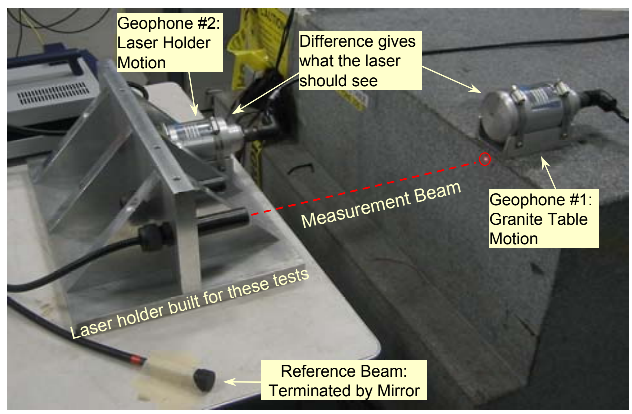

Fig. 3 Measurement set up for performance test of the laser system used in the single beam mode.

Fig. 4 shows the results of the single beam measurements. It can be seen that the power spectrum of the laser signal matches very well with that derived from

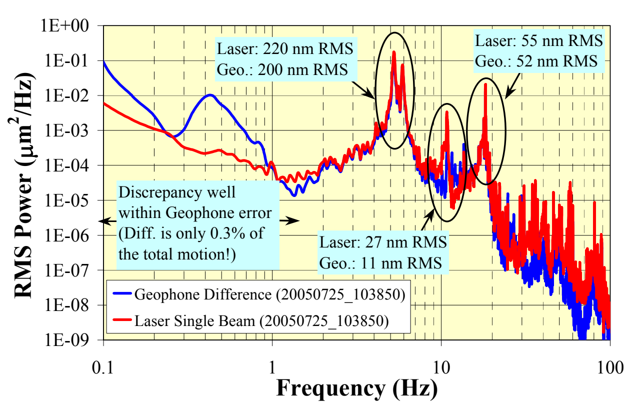

Fig. 4 Comparison of the power spectra measured by the laser system in the single beam mode with that expected from a difference of the two geophone signals.

the two geophone signals. The total RMS motions at the prominent peaks are indicated in Fig. 4. At frequencies below 1 Hz, both the granite table and the laser holder have correlated motions. The difference is only a small fraction of the total power. The geophone subtraction is not very accurate in this case due to limited calibration accuracy, as well as drop off of the geophone sensitivity below the 1 Hz resonance frequency.

In the single beam performance test described above, the total motion of the laser holder with respect to the object being measured (the granite table) was more than 200 nm RMS integrated above 1 Hz. If the dual beam mode is used to measure the relative motion of two objects that have nearly identical motion, it is expected that the motion of the laser holder itself with respect to the object will not affect the measurements. However, in practice, the effect of laser holder motion may not be completely eliminated. In order to test the performance of the laser system in the dual beam mode, we mounted both laser heads on the specially built holder and measured the relative motion of two spots near each other on the side of the large granite table, as shown in Fig. 5. Under the assumption that the relative motion of the two laser heads is negligible, and the assumption that the relative motion of the two spots on the granite table is negligible, the dual beam data should essentially give zero motion.

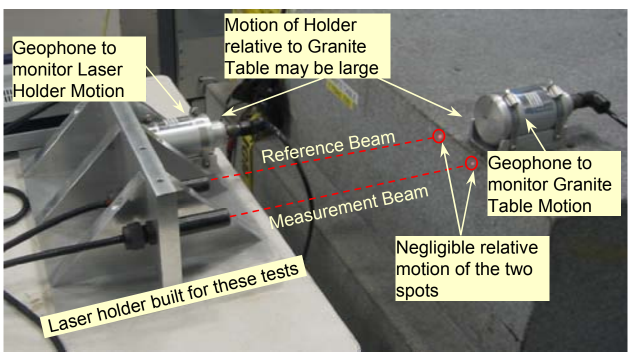

Fig. 5 Measurement set up for performance test of the laser system used in the dual beam mode.

Fig. 6 shows the power spectra for the relative motion of the laser holder with respect to the granite table (derived from geophones data) and the relative motion of the two spots measured with the laser in the dual beam mode. It can be seen that several of the prominent peaks in the geophones data are also present in the dual beam spectrum. However, the amplitudes are suppressed by a factor of 10 or more. The total motion, integrated over 1 Hz and above, is 220 nm RMS for the holder relative to the granite table, and is 17 nm RMS for the dual beam data. These results show that while there is a significant suppression of the laser holder motion in the dual beam mode, it is still desirable to keep the holder motion as small as possible. There is also a peak (~10 nm RMS) at 10.6 Hz, which is not suppressed at all in the laser dual beam data. This motion is entirely from the laser holder, since it is seen in the geophone data on the holder, but is absent from the geophone data on the granite table.

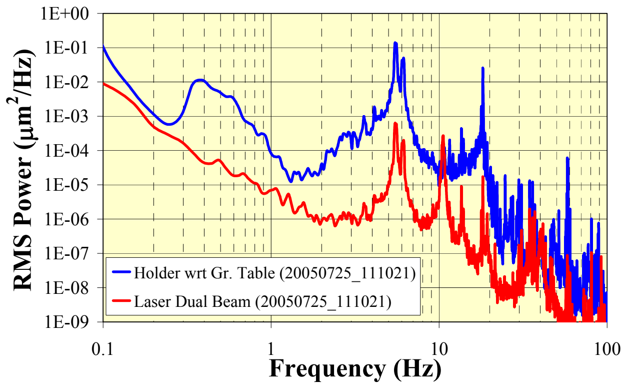

Fig. 6 Demonstration of the suppression of the laser holder motion in the dual beam data.

RHIC QUADRUPOLE TEST SET UP

The RHIC quadrupoles are assembled along with a corrector package and either a sextupole or a trim quadrupole in a single cold mass assembly, referred to as a CQS assembly [2]. For the purpose of these tests, we have used a spare RHIC CQS assembly in a cryostat. Viewports needed to shine the laser beam on the cold mass were installed in large bellows that were used to connect the cryostat to the cryogenic system of the test stand. In order to minimize transmission of high frequency vibrations from the test stand to the magnet, the magnet was mounted on isolation mounts with a resonance frequency of 3-4 Hz, as shown in Fig. 7. These mounts worked well in initial warm tests when the magnet was not hooked up to the cryogenic system. However, the bellows proved to be stiff enough to couple test stand motion to the magnet and the isolation mounts were not very effective once the bellows were in place.

For measurements of the horizontal motion, a holder for the laser heads was built and installed on the test stand, as shown in Fig. 7. The holder has platforms for geophones

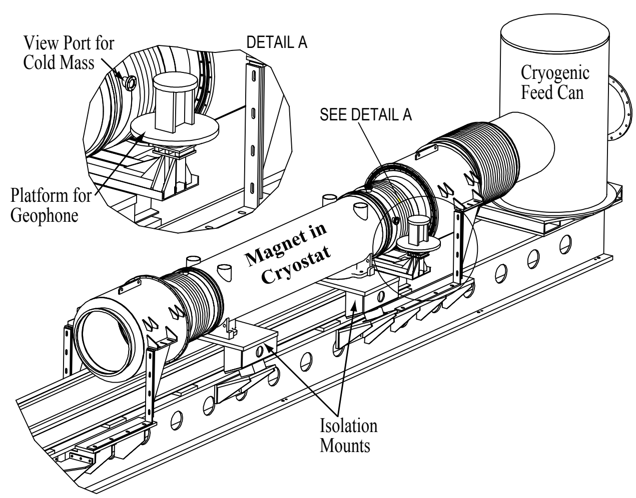

Fig. 7 RHIC quadrupole on the cold test stand and the laser holder for measurements of the horizontal motion.

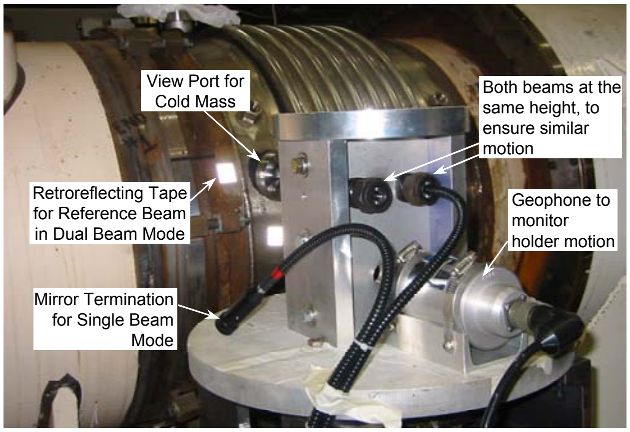

Fig. 8 Set up for the measurement of the horizontal motion of the RHIC quadrupole cold mass.

that were used to monitor the motion of the holder itself. The two laser heads were mounted at the same height, as shown in Fig. 8, to ensure negligible relative motion of the two arms, even though the motion of the holder itself (~300 nm RMS, integrated above 1 Hz) was not very small. The suppression of the laser holder motion in the dual beam mode was verified once again by carrying out measurements on an aluminum plate clamped to the view port. The relative motion of the plate and the laser holder was ~250 nm RMS, integrated above 1 Hz, as measured using the single beam mode. In the dual beam mode, the relative motion of the two adjacent spots on the aluminum plate was measured to be ~40 nm RMS, integrated above 1 Hz. It should be noted that at least some part of this motion might indeed be true relative motion of the .two adjacent spots on the aluminum plate. In any case, this "background" was well below the actual relative motion of the cold mass and the cryostat.

A slightly different holder design was used for measuring the vertical motion. The laser beam entered through a view port at the top of the bellows on the end opposite to the horizontal set up (the end away from the cryogenic feed can). The laser heads were attached to holders mounted on sturdy aluminum frames mounted to the test stand, as shown in Fig. 9. A geophone was used to monitor the vertical motion of the holder itself, which

Fig. 9 Set up for the measurement of the vertical motion of the RHIC quadrupole cold mass.

was ~250 nm RMS, integrated above 1 Hz. The performance of the laser system was also checked for this configuration by shining the laser beam on an aluminum plate attached to the viewport, as in the case of the horizontal motion. The relative motion of the plate and holder was measured to be ~200 nm RMS, integrated above 1 Hz, using the single beam mode. In the dual beam mode measurement, the relative motion of the two adjacent spots on the aluminum plate was ~45 nm RMS, integrated above 1 Hz. This is comparable to what was obtained for the horizontal set up.

MEASUREMENT PLAN AND ANALYSIS

The magnet was hooked up to the cryogenic system and cooled down to 4.5 K. Measurements of the horizontal and the vertical cold mass motion were first made in both the single beam and the dual beam modes with the cryogens flowing. Three independent sets of data were acquired in each case at a scan rate of 1600 Hz for a duration of 143.5 seconds. Analysis was done in block sizes of 16K data points (~0.1 Hz resolution), with 8K overlap. All the power spectra obtained in this way (27 subsets per run, 81 spectra total) were then averaged for better statistics. The total RMS motion above a certain frequency, *f*, was obtained by integrating the power spectra from *f* to infinity, and taking the squre root of the integral. We will refer to the plots of such RMS motion as a function of frequency as the *integrated spectra*. A set of three measurements was then made with the cryogen flow stopped and a wait of about 30 minutes. Finally, the cryogen flow was resumed, and the measurements were repeated in order to unambiguously correlate any changes in the spectra to the presence of cryogen flow.

RESULTS

The integrated spectra for the horizontal motion in the single beam mode are shown in Fig. 10. These spectra represent the motion of the cold mass with respect to the laser holder. The RMS motion above 1 Hz is rather large, over 400 nm, with a dominant peak around 30 Hz. The single beam measurements are sensitive to the motion of

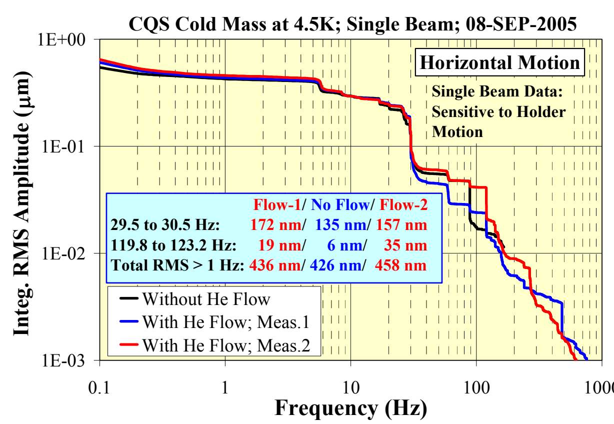

Fig. 10 Integrated spectra for the horizontal motion, as measured in the single beam mode.

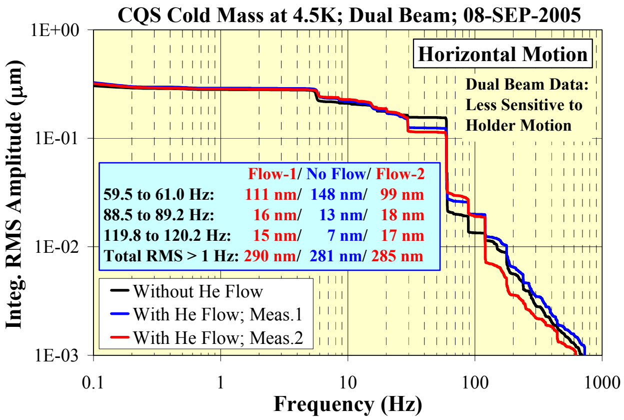

Fig. 11 Integrated spectra for the horizontal motion, as measured in the dual beam mode.

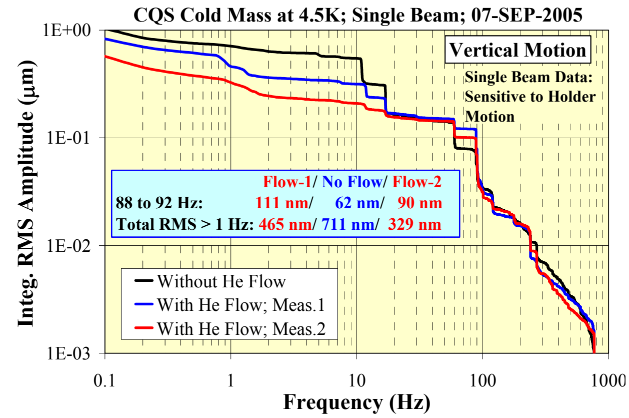

Fig. 12 Integrated spectra for the vertical motion, as measured in the single beam mode.

the laser holder itself, which was ~300 nm RMS integrated above 1 Hz. The RMS motions for some of the dominant peaks in the spectra are also tabulated in Fig. 10. A comparison of the spectra for the cases of with and without helium flow shows only a minor increase (less than 30 nm) for the 120 Hz peak. The overall motion above 1 Hz is also slightly less without helium flow.

The integrated spectra for the horizontal motion measured in the dual beam mode are shown in Fig. 11. These spectra represent the motion of the cold mass relative to the cryostat (strictly speaking, relative to the body of the bellows, which are attached to the cryostat). The dual beam measurements are relatively insensitive to the holder motion, but are sensitive to the cryostat motion. The RMS motion above 1 Hz is ~290 nm in this case, and is significantly lower than in the single beam mode. The 30 Hz motion is much lower than the single beam case, but the 60 Hz motion is much larger. This indicates that the 30 Hz signal in the single beam mode is perhaps dominated by the holder motion, whereas the 60 Hz motion in the dual beam mode is dominated by the cryostat motion. The data from the geophones, taken concurrently with the laser vibrometer data, also confirm this. As in the case of the single beam data, the dual beam data also show that there is no significant increase in the RMS motion above 1 Hz. The increase in motion at 120 Hz due to helium flow is more consistent in the dual beam data, and is ~10 nm. There is also an increase of less than 10 nm at 90 Hz.

Fig. 12 shows the integrated spectra for the vertical motion of the cold mass relative to the laser holder, measured using the single beam mode. Surprisingly, the total motion above 1 Hz is much more in the case of no helium flow, as compared to the two measurements with helium flow. The increased motion for the no helium flow case largely arises from two strong peaks at ~11 Hz and ~17 Hz. An examination of the geophone data for the laser holder and the cryostat shows that the 11 Hz peak is almost entirely from the magnet motion, whereas the 17 Hz peak comes partly from the holder motion and partly from the magnet motion. The motion at these frequencies was found to vary a lot with time. For example, these peaks are almost nonexistent in the measurements after the helium flow was resumed (red curve in Fig. 12). If we ignore these peaks, then the only prominent peaks remaining are at ~60 Hz and ~90 Hz. The motion at 60 Hz is insensitive to helium flow, but the 90 Hz motion is clearly less with the helium flow stopped.

The integrated spectra for the vertical motion measured in the dual beam mode are shown in Fig. 13. The large step in the single beam spectrum at ~11 Hz is practically non-existent in the dual beam data, and the step at ~17 Hz is also much smaller. The dual beam spectra are mostly independent of helium flow, except for a slightly larger motion at 60 Hz in the case of no helium flow.

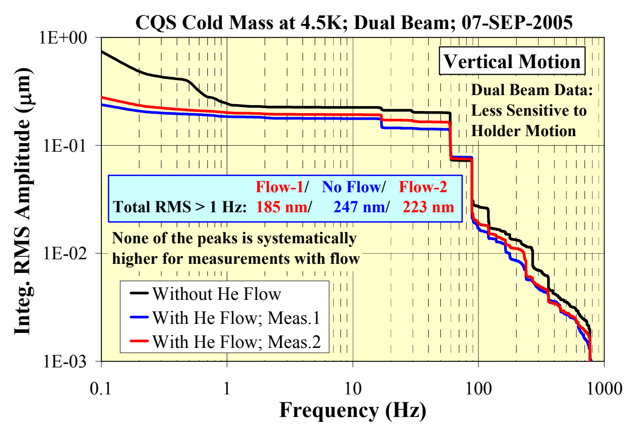

Fig. 13 Integrated spectra for the vertical motion, as measured in the dual beam mode.

In view of the large run-to-run variations in the amount of motion at 11 Hz and 17 Hz, the measurements of vertical motion were repeated on the next day. However, only one set of measurements was made with the helium flowing, instead of two. Figs. 14 and 15 show the integrated spectra in the single and the dual beam modes respectively. The single beam spectrum measured with the helium flowing shows significant motion at 7.5 Hz, 11 Hz and 17 Hz. However, the spectrum without helium flow is now relatively clean, except for a small step at

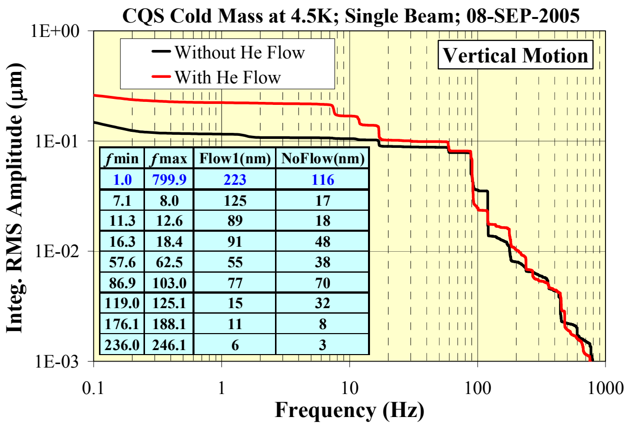

Fig. 14 Integrated power spectra for the vertical motion, as measured in the single beam mode on a different day.

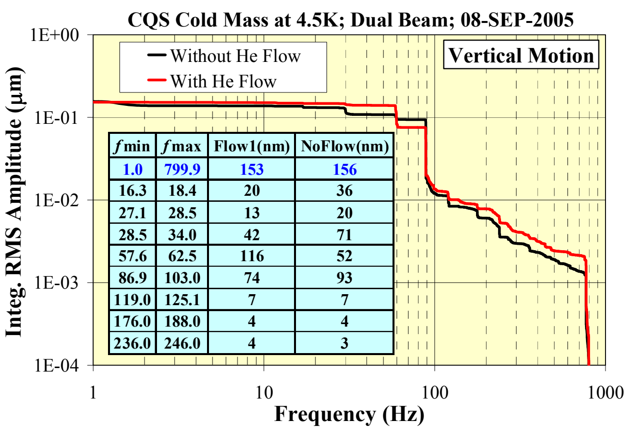

Fig. 15 Integrated power spectra for the vertical motion, as measured in the dual beam mode on a different day.

17 Hz. These results are in sharp contrast to the single beam data taken on the previous day, shown in Fig. 12. On the other hand, the dual beam data in Fig. 15 show very little overall difference with and without helium flow. This is generally consistent with the results on the previous day (Fig. 13), except at 60 Hz. The 60 Hz motion was slightly less with helium flow on the previous day, but is more on the next day. Thus, the influence of helium flow on the vertical motion could not be established unambiguously in this study. Further data, perhaps with multiple cycles of measurements with and without helium flow, are needed to further resolve this.

CONCLUSIONS

The vibrations in a superconducting RHIC quadrupole have been measured with and without helium flow in order to investigate the effect of cryogen flow on the magnet stability. Performance of a laser Doppler vibrometer used for these measurements was studied in detail, and was shown to be satisfactory. For the horizontal motion, where the magnet is relatively free to move, the flow of helium increases the motion at a few frequencies by ~10-30 nm. For the vertical direction, where the magnet is supported by insulating posts, no conclusive evidence of either an increase or a reduction in the motion with helium flow could be established in the single beam data. For the dual beam measurements, which provide the relative motion of the cold mass with respect to the cryostat, no systematic increase in the vertical motion was observed with helium flow, except for a significant increase at 60 Hz in some runs. Further measurements are needed to help resolve the issue of vertical motion with better certainty. Finally, the absolute motion of the magnet is rather large, which limits the sensitivity and accuracy of these measurements. It will be desirable to carry out similar studies in magnets that are better stabilized. Despite the limitations of this study, these results appear quite encouraging for the use of superconducting technology for the quadrupoles in the final focus region of the ILC.

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